

# VISION SPACEPORT

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## RENEWING AMERICA'S SPACE LAUNCH INFRASTRUCTURE & OPERATIONS



Vision Spaceport artwork by Pat Rawlings/SAIC

- » FINDINGS
- » A VISION OF IMPROVEMENT
- » SUMMARY OF RESEARCH ACTIVITY

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This report summarizes the R&D activity of the Vision Spaceport Project from 1998 through 2000 and coincides with the first release of the *Strategic Planning Tool*. In addition to providing top-level findings, the NASA Technical Manager provides a long range, “quick-look” vision of ground infrastructure and operations for future space travel.

Many individuals have contributed to this effort. Their vision, innovativeness, patience and dedication to explore and build on largely uncharted ground is here acknowledged and appreciated.

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(and many UCF students-great job!)

To access more information on the Vision Spaceport Project, go to: <http://www.visionspaceport.org>

For information on spaceport technology, in general, go to:

<http://www-pao.ksc.nasa.gov/kscpao/spacetech/>

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# VISION SPACEPORT

## *Renewing America's Space Launch Infrastructure & Operations*

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### EXECUTIVE SUMMARY

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#### OVERVIEW

In July of 1998, the National Aeronautics & Space Administration's (NASA) John F. Kennedy Space Center (KSC) approved the Vision Spaceport Project. A partnership formed by NASA, industry and academia has since pursued the modeling and analysis of spaceport functions.

The primary intent has been to build tools for strategic decision-makers while formulating an exciting new vision for space transportation ground operations. The tools allow decision-makers to review proposed concepts and prioritize technology investments. In general, the tools provide a strategic framework for space transportation and spaceport planning. The two-year effort has fulfilled its initial objectives, which include:

- 1) *Benchmarking fundamental space transportation system cost and performance relationships*
- 2) *Outlining the structure of a comprehensive spaceport knowledge-base and building strategic decision-support tools*
- 3) *Rendering a shared vision of highly productive spaceports of the future*
- 4) *Creating a structured process for exploring advanced concepts and spaceport technologies*

#### CONCLUSION

The output and efficiency of space transportation infrastructure is in stagnation at best. However, a knowledge-base of space system design characteristics and operations concept choices has been assembled and incorporated in a user-friendly tool by a government/industry team to help improve the trend. The principal products of this project (particularly the *Strategic Planning Tool-Release 1* and the spaceport technology assessment tools) are a major advancement in the state-of-the-art for analysis and modeling of space transportation systems. It is becoming clear from our research into modeling space launch systems and spaceport technologies that these products can help shape an important strategic framework for the industry and for our nation.

Vision Spaceport's technology planning products, along with recent Office of Science & Technology Policy (OSTP) recommendations for management planning, are key strategic elements. Still needed to round out a total strategic framework, however, is an overall approach to National Space Launch Growth. As the report will show, much groundwork has been completed to aid in planning the renewal, and in the longer-term, revolutionizing America's space launch capability.

## PRIMARY FINDINGS

After considering the accomplishments, as well as the barriers confronted in our research, the following top-level findings are forwarded by the NASA Technical Manager:

**FINDING 1: Understanding the cost and performance of operational ground infrastructure, and the associated operations, is critical to creating effective space transportation architectures.** The most relevant and hard-hitting metrics are:

- A. *Capital investment costs and fixed operating costs for facilities and equipment*
- B. *Variable costs (relating to flight rate) of labor, materials and other direct costs*
- C. *Cycle Time and Throughput*

Without such insight, many misleading notions will remain of the true extent and nature of ground support infrastructure (facilities, equipment, logistics, workforce, utilities, etc.) and the associated operational performance.

**FINDING 2: A key performance metric of any transportation system is throughput (as measured by annual cargo and passenger rates, for example—see *Figures 1 & 2*). Modeling throughput efficiency can significantly lower the cost-per-pound, and yet this important parameter remains unaccounted for in NASA's Strategic Plan.**

*Traditional operations models, however, have treated throughput and flight rate as an assumed input and then allocated these to facility-based processes. Our modeling methodology has overcome this shortfall through its analytical capability. Based on design characteristics as inputs, the method determines flight rate as an output that is available for economic trades and analysis. This modeling technique ultimately yields an understanding of the influences between design characteristics and the responsiveness and affordability of various concepts.*

**FINDING 3: An independent assessment of our software tool methodology by civil and military government technologists, industry designers and operators and academia representatives, found it to give credible yet limited results.** Specifically,

- A. *Industry found the model predictions “quite credible” when examining existing systems (Shuttle, Titan and Atlas) and “accurately assessed the operability improvements” that have been implemented in those systems over the last 10 years.*
- B. *While the methodology of the tool appears sound, development of the tool's output capability would greatly increase its usefulness and applicability.*
- C. *Academia found a great deal of potential in our software tool to draw interest in the field of ground systems and technologies. This is perhaps because students can now interact with advanced space flight systems and observe connections with the resulting ground architecture. We found the same sense of academic excitement and interest as we explored spaceport visualization techniques.*

**FINDING 4: The team identified several top-level spaceport modeling technology challenges to pursue in NASA's Space Launch Initiative.**

- A. *Activity-based modeling of Launch Infrastructure & Operations (cost & throughput)*
- B. *Integration of our methodology with collaborative, multi-disciplinary space transportation design environments*
- C. *Allocating the results of top-level operations and infrastructures estimates to lower-level functional tasks and facility objects*
- D. *Intelligent visualization of entire Spaceport Concepts—Rendering form from function*



**FINDING 5: Exploration of technology prioritization techniques is important to pursue for modernization and healthy growth in spaceports.**

*Promising areas needing more analysis and concept exploration in the near term include spaceport information systems, sensing & instrumentation, and command & control systems. Additionally, payload standardization, automated checkout, and carriers/container methods need more exploration to identify specific technology shortfalls to achieve realistic “ship & shoot” concepts.*

**FINDING 6: The results of Vision Spaceport’s benchmarking line of research indicate that excess launch capacity probably exists. This unused and un- financed capacity has the potential to extend and defend the nation’s commercial, civil and military space launch capabilities in the near term. Therefore, using the capacity for innovative non-traditional applications can highlight the benefits of investing in new space markets and missions.**

**FINDING 7: The inherent reliability and dependability of flight and ground systems, across nearly all technical disciplines (fluid, electrical and mechanical) needs much more investigation, needs to be more widely communicated, and more importantly, needs far more engineering attention.**

Our strategic planning tool reveals that such characteristics as design life, components with demonstrated reliability, operational system margin, total system parts counts, number of fluid and electrical connections, correlate to many spaceport cost centers. For example, routine flight and ground component removals lead to excessive logistics costs, unplanned work and lengthy cycle times for turnaround and launch. As *Figures 1 & 2* show, this in turn affects system throughput efficiency, and thus the cost per pound.

Further, the subject of system dependability (flight and ground systems) is highly related to the subject of system certification for flight. Low levels of confidence gained from flight and ground operations experience leads to 1) a high degree of test and checkout, 2) large levels of unplanned work and elevated logistics costs, 3) lengthy, repeated, time consuming, and expensive flight-by-flight certifications, finally resulting in 4) a very large sustaining engineering workforce. Higher levels of demonstrated reliability and dependability would greatly reduce the sustaining engineering workload and lead to vehicle type-certificates. *However, specific technical means for creating a structured system certification process are not being pursued—nor are the necessary ground and flight test infrastructure being established.* NASA may wish, for example, to consider a new technology readiness level—TRL10 (see *Figure 3*).

**FINDING 8: We must renew and re-establish the importance of our systems engineering capabilities and begin by identifying specific impediments to improving our space launch systems (technical and programmatic, real and perceived).**

Results of work being performed by the Space Propulsion Synergy Team (SPST) to create a knowledge base of these impediments (and candidate solutions that address these impediments) is acknowledged here as a important national systems engineering activity.

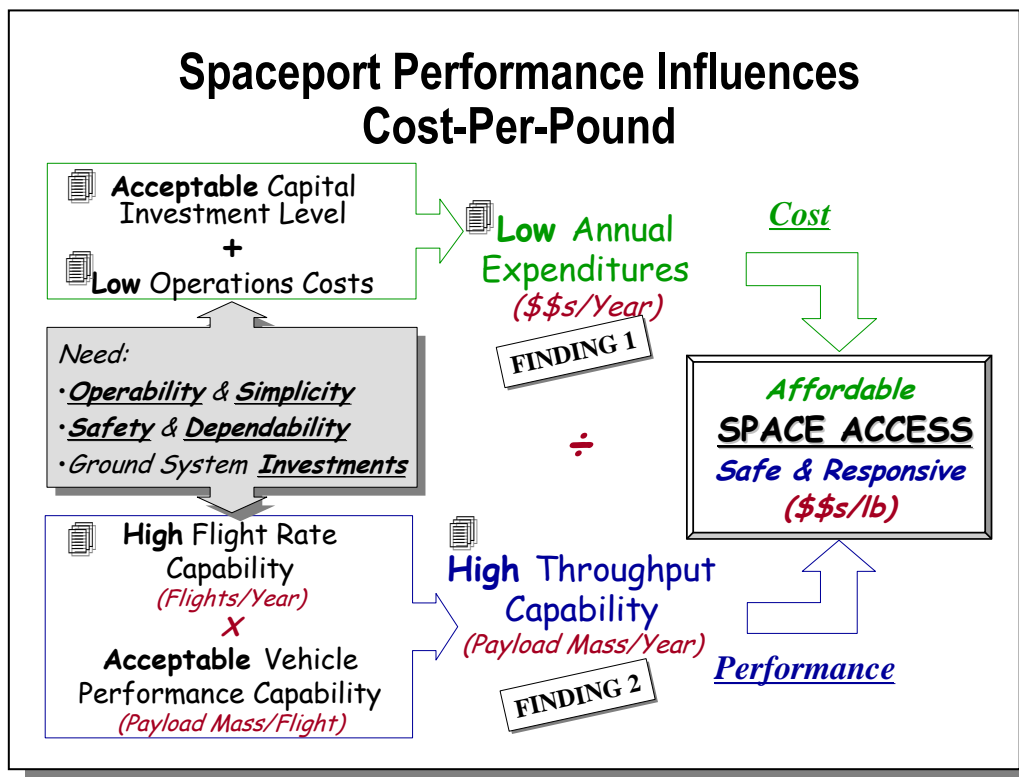


FIGURE 1—Understanding cost-performance relationships forms the basis of the Vision Spaceport approach to deriving Affordable, Safe and Responsive Access-to-Space

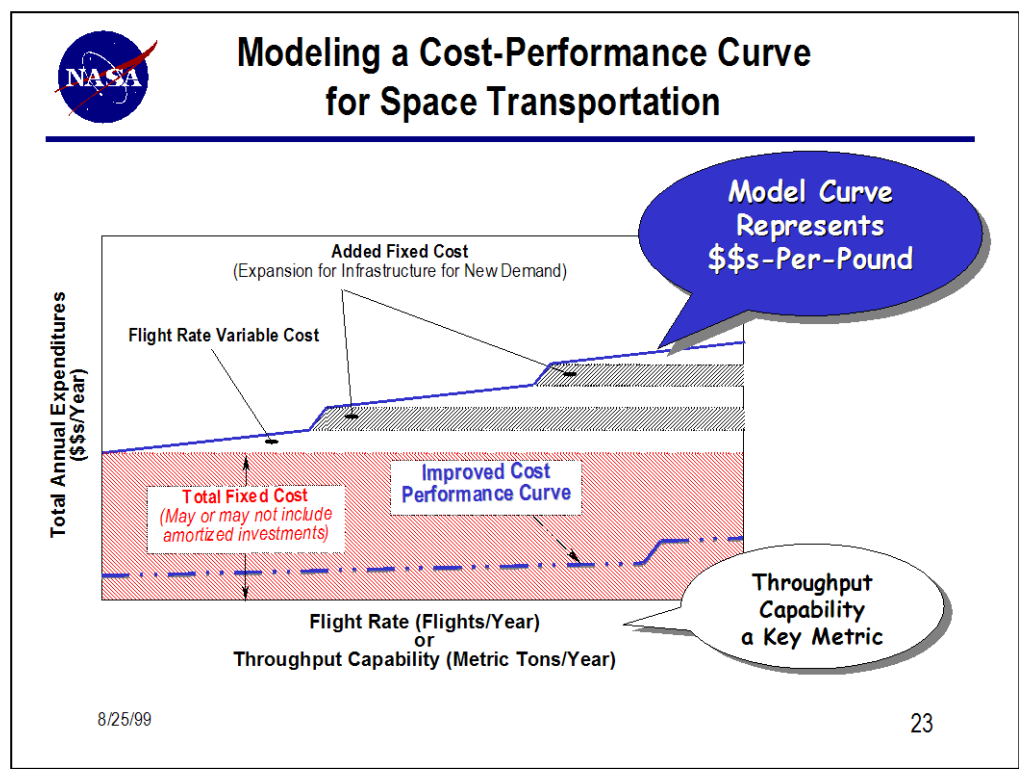


FIGURE 2—Notional “cost-performance curve” models important attributes of an operational system—and its potential for healthy growth. It requires knowledge of the full extent of the infrastructure.

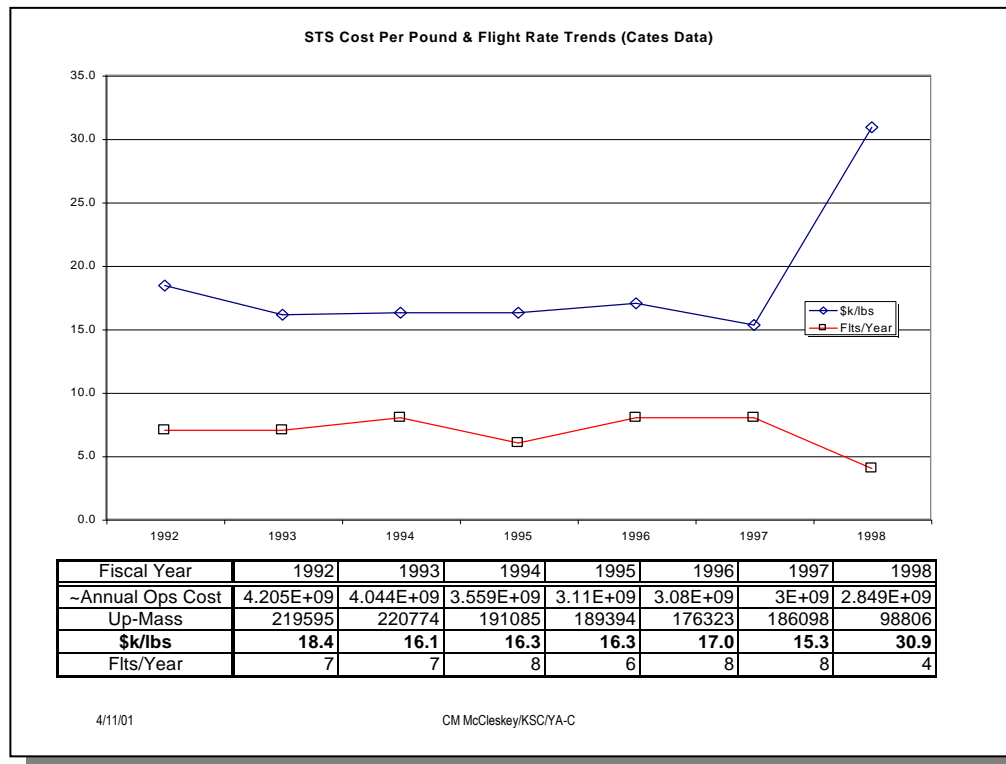


FIGURE 3—This plot of actual Shuttle cost-per-pound performance, as calculated by the ratio of the annual costs to the annual throughput performance, demonstrates sensitivity to flight rate

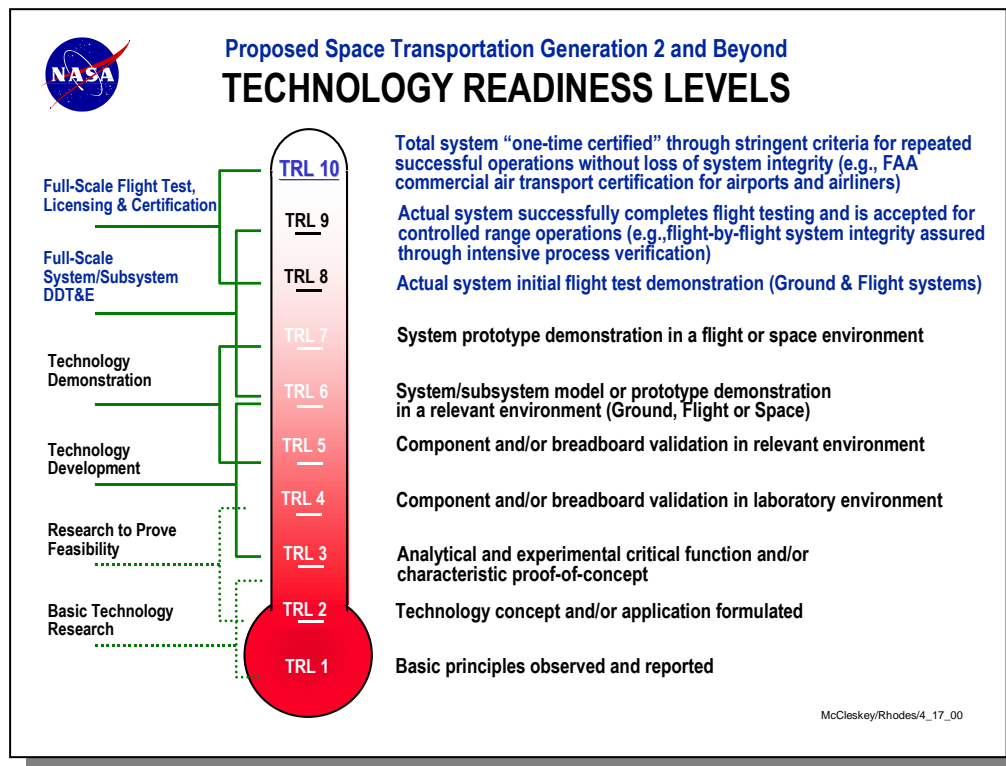


FIGURE 4—The Strategic Planning Tool reveals that improving reliability and dependability of flight and ground systems may lead us to recognize a new technology readiness level—Full-scale flight test, licensing and certification



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# VISION SPACEPORT

## PROJECT OVERVIEW

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### INTRODUCTION

#### MOTIVATION FOR RESEARCH INTO SPACEPORT OPERATIONS & INFRASTRUCTURE

In 1997, NASA concluded the Highly Reusable Space Transportation (HRST) study. The study indicated that certain ground technology and process investments are important to operate future vehicles cheaply and safely. The study recognized familiar technologies, such as integrated vehicle health management, robotics, and nondestructive inspection and evaluation. However, the more subtle systems engineering goal of requiring operations considerations to drive all vehicle design and technology investment decisions, and not performance for its own sake, was the more significant finding.<sup>1</sup>

Among the HRST study participants were a group of government and industry personnel experienced in launch site analysis, advanced space transportation concepts and technology development, design and operations. While the study's objectives stretched far into the future, it was recognized that fundamental principles from past launch operations concepts and designs are very important to apply.

*With better than 20 years' experience, the von Braun team preached and practiced that rocket and launch pad must be mated on the drawing board, if they were to be compatible at the launching. The new rocket went hand in hand with its launching facility.*

Moonport: A History of Apollo Launch Facilities & Operations,  
*Charles D. Benson & Wm. B. Faberty, 1978*

The above observation, made nearly a quarter century ago about a previous generation of space pioneers, is a seemingly obscure detail written in the history of America's space program.<sup>2</sup> The implication that there are complex relationships that exist between all flight and ground systems is profoundly true.

Note in *Figure 5* on the next page, for example, the physical models presented to the national leadership<sup>3</sup>. They convey that the entire Apollo-Saturn operations concept and infrastructure was coming together from both a flight and ground system sense. Presented were not only the Saturn-Apollo vehicles, but also the radically new large-scale mobile launch concept with its massive vehicle assembly building, transporters and mobile launch tower. In total, presenting the ground support infrastructure showed that a total architecture was coming together. The figure also shows that management of launch infrastructure and operations (embodied in Dr. Debus of the Launch Operations Center, later KSC) was "front and center." For that reason Dr. Debus held one of only four seats in NASA's Apollo Management Council.

The previous century of aeronautical engineering required achieving great strides in flight system performance. Great investments were needed for the development of fragile lightweight components, powerful propulsion systems with relatively little margin, and creation of complex custom guidance and navigation methods, to name but a few. Today's space policies, however, ask for improvements in affordability, safety, responsiveness and reliability.<sup>4</sup> In order to comply with these policies, the difficult task of ensuring flight-to-ground system compatibility, from concept through operation, goes beyond satisfying the physics of the flight systems. It requires a renewal of our systems engineering capabilities, as well as inclusion of many other technical and non-technical disciplines.



FIGURE 5—National Leadership Motivated to Create the Apollo-Saturn Launch Infrastructure & Operations Capability

The Vision Spaceport Project proceeded with the idea that analytical models can be developed to represent the more important interactions that must be dealt with very early in the design life cycle—in fact, even before concept commitment.

There is an urgent need for a means to relate drivers of launch infrastructure and operations to the resulting cost and flight rate capability. It was recognized that without such a tool, designers would continue to struggle weighing and considering difficult trades between the needs of the operator and investors as well as satisfying the physics of space travel. As long as there are no accepted analytical tools, no hard-hitting metrics, no systems basis for opening up the trade space to operationally efficient options, then the operations community would continue to be held responsible for the lack of investment in space launch infrastructure and operations. Vision Spaceport set out to confront this challenge.

Later in the project, the team was also asked to confront the technology challenges associated with revolutionary improvements in ground system performance. The government-industry team undertook a systematic review of the desired attributes, spaceport systems and design drivers of ground equipment, ground facilities and ground operations.

Finally, the team has recognized that the time has come for the operations community to take stewardship of their craft and engage the academic community. Involvement of university students and faculty occurred during the research.

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## VISION SPACEPORT JOINT SPONSORED RESEARCH

The project team found an innovative mechanism for performing the proposed joint research and technology project. Based on NASA's Space Act<sup>5</sup>, the Joint Sponsored Research (JSR) Program allows NASA center directors to provide resources on a shared or pooled basis to commercial and/or nonprofit partners.

### *The JSR Program*

The JSR Program is dedicated to promoting R&D partnerships between NASA and the private sector pertaining to dual use technologies and to commercially valuable technologies with industry-wide application. The Joint Sponsored Research Program goals are to accelerate technology development, maintain U.S. technological leadership, foster U.S. economic growth and competitiveness, and/or create jobs.<sup>6</sup>

In 1998, an informal consortium (the Spaceport Synergy Team), sent out an invitation to potential partners and created a formal partnership. The Vision Spaceport Project was created in order to pursue the research objectives outlined in this report and forward a shared vision of improvement for space transportation. The initial partners were: NASA's John F. Kennedy Space Center; the Ames Research Center; McDonnell Douglas, A Wholly Owned Subsidiary of the Boeing Company; Lockheed Martin Corporation; Command & Control Technologies (CCT) Corporation; Pat Rawlings, space concept artist for Science Applications International Corporation (SAIC); and the University of Central Florida's (UCF) Institute for Simulation & Training (IST).



FIGURE 6— *Vision Spaceport Partners at the Signing Ceremony, July 1998*

## A VISION OF IMPROVEMENT FOR SPACEPORT OPERATIONS

In this section, a summary vision for space launch systems and operations will be shared. The basis for this began in 1994 with a challenge from the government/industry Operations & Avionics Synergy Team during the concept definition phase of NASA's X-33 program. The product was at that time known as the Reusable Launch Vehicle (RLV) Operations Concept Vision; that is, a generic "plain vanilla" operations concept for future reusable launch architectures<sup>7</sup> that was shared by NASA KSC and its industry partners.

Later, during NASA's HRST Study (1995-97), a similar challenge to the Spaceport Synergy Team produced a "catalog" of generic spaceport functions—or, in other words, a generic definition for spaceport infrastructure and operations functions. Taken together they began to form a "spaceport" vision. While the vision statement was not accepted in the X-33 program proposal, it was carried into the formal partnership as a preamble to the research agreement.

### A Vision of Spaceport Operations

A vision of improvement for spaceport architectures and operations is being pursued by the parties of this Joint Sponsored Research Agreement. This ten-point operations concept vision was developed from the experience gained during a variety of previous space transportation programs. It was initially inspired by the National Space Transportation Policy goal of achieving "reliable and affordable access to space". Since its creation in 1994, this policy goal has been vigorously pursued in the U.S. with enterprise and ingenuity. New launch vehicles designs, investments and growth in space markets, the privately funded "X-Prize" Foundation program to fly the first space tourists, as well as interest in new commercial spaceports, inspire us to continue to enable this vision.

1. Provide a simplified, very-highly automated vehicle enabling minimum periodic and repetitive maintenance (airplane-like) and resultant short turnaround time between flights (hours not months).
2. Strive to isolate vehicle ground processing from dependence on facilities and ground support equipment (GSE). Routine, scheduled turnaround should replenish consumables only.
3. Promote advanced technologies and develop vehicle health management systems and self-test capabilities at a level which informs the operator only of the required corrective action prior to next flight. Let the vehicle "talk" to the operator remotely during processing. Incorporation of special vehicle engineering instrumentation will be on specifically designated technology demonstration vehicles only. Satisfaction of certification criteria will remove the requirement on operational vehicles.
4. Eliminate "flight readiness-style" vehicle re-certification for every operational flight. Provide aircraft-style, vehicle-type certificate for repetitive commercial flight operations.
5. Design-in performance margins and flight hardware allowances to eliminate processing impact, i.e., strive to design-out and eliminate unscheduled work. Flight operations are very highly autonomous by design. No dedicated software flight design function is required to support each flight.
6. Reduce operations and hardware complexity for maximum utilization of resources and eliminate opportunity for human-induced systems failures: Less "hands-on" activity, less human error.
7. Employ near autonomous ground management planning at top levels. Focus on automatic, interactive scheduling of on-line flight vehicle activity, ground support facilities, as well as off-line supporting logistics services.
8. Adapt minimum standardized payload interfaces to assure maximum flexibility and affordability for the space launch customer. The most affordable vehicle to operate will be blind to payload needs; like a truck. Eliminate payload impact on the launch vehicle system infrastructure.
9. Ensure that space launch architectures are built through synergistic processes (i.e., creation of new space launch capabilities) drawing from the talents of various flight system design disciplines (propulsion, structures/mechanisms, avionics and payloads), as well as operations (vehicle, payloads and logistics engineering).
10. The role of engineering (technology creation, conceptual design and advanced development) during the operational era will be to perform continuous improvement and technology advancement for future market-driven needs and government requirements for the human exploration and development of space.



## NEW SPACEPORT ARCHITECTURES FOR A NEW CENTURY OF SPACE TRAVEL

As we begin to conceive of new space vehicle concepts, advanced ground infrastructure and operations concepts will need to emerge, as well, to fulfill our Vision of Spaceport Operations.

For example, various approaches for ground launch assist are now being explored, such as the MagLev concept. Also, how can we produce, distribute, condition and load the massive amounts of propellants that will be needed for advanced spaceliners that are to fly every day, or even multiple times per day at the spaceport? Today, with modest flight rates requiring modest amounts of propellant, commodities such as cryogenic hydrogen, liquid oxygen and liquid nitrogen are trucked into many different space launch complexes and loaded into large spheres (or dewers) at the launch pad. Advanced concepts for generation of both propellant commodities and commodities for industrial and commercial consumption, such as electricity and water, have been studied in recent years.<sup>8</sup>

Another aspect of master planning of spaceports will involve synthesis of many different modes of transportation, such as ground transportation (road and rail), sea, and air travel. Space will become a new dimension in our national economy when our current transportation nodes make frequently scheduled connections, literally, to space from our national spaceports. Passenger space travel becomes possible with safe and affordable space access made possible by engineering highly dependable flight and ground systems.

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*Space will become a new dimension in our national economy when our current transportation nodes make frequently scheduled connections, literally, to space*

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## A VISION FOR SPACE CARGO SHIPPING & RECEIVING

Currently, the process of installing and off-loading space payloads is a complex task. On the Shuttle Orbiter, for example, the process is one of redesigning the payload bay and crew compartment for each flight. This is due to many fluid hook-ups, routing of air or nitrogen gas purge ducts, electric power connections, routing of signal cables, and specialized structural mating operations (such as positioning of special keel fittings and trunnions, and tailored thermal insulation blankets). This process is often referred to as *payload integration*, that is, the rather complex mating of the payload both physically and functionally to the launch vehicle. Often, this operation is performed in cleanliness-controlled environments with manual labor forced to don special garments, and adhere to restrictive clean room operations.

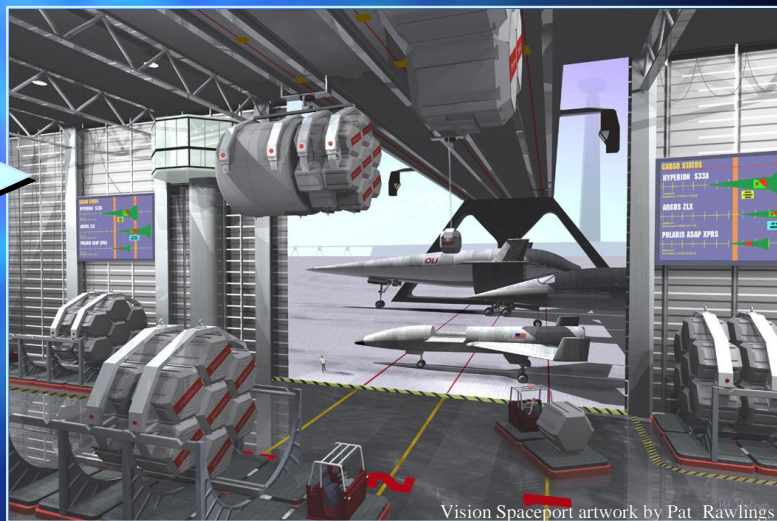
Unlike the air cargo or the sea-going cargo transportation systems, space transportation has no agreed upon standard for easy-to-load containers. Perhaps it will take a renewed purpose in space to generate a higher cargo demand before there will be a requirement for such a standardization. This is, however, the vision.

The 1994 *RLV Operations Concept Vision* called for adoption of minimum standardized payload interfaces (and preferably none other than a simple mechanical attachment taking just minutes to complete). This was to assure maximum flexibility and affordability for the space launch customer. More importantly, it would greatly enhance, even revolutionize, the throughput efficiency of space transportation vehicles and their spaceports. The most affordable vehicle to operate is blind to payload needs—like a truck, and not like a patient in an ambulance. Overall, the vision would strive to eliminate the payload impact on the launch system infrastructure.

### From Payload Integration to Space Cargo Shipping & Receiving



*Payload Integration*



*Vision Spaceport artwork by Pat Rawlings*

*Highly automated, responsive and affordable shipping & receiving*

## A VISION FOR SPACE TRAFFIC & FLIGHT CONTROL

Currently, the launch and flight control operations are extremely manpower intensive with massive monitoring of many individual subsystems and processes. Public safety, flight crew safety, as well as the integrity of the vehicle functions for flight are all carefully planned and monitored.

To overcome this customized, time consuming and expensive set of infrastructures, the 1994 *RLV Operations Concept Vision* called for several advances. First, it promoted new technologies and the development of health management systems that would let the vehicle “talk” to the operator remotely during processing. This would put a greater up-front burden on the vehicle designer, but would avoid the recurring time consuming hook-ups of ground-based test equipment, performance of manual leak checks, and generally avoiding the many unplanned guessing games that occur in isolating bad components. Also, in this vision, custom flight planning functions are kept to a bare minimum to insure greater vehicle availability for space access, and an overall higher system throughput capability.

Incorporation of engineering instrumentation would be on specifically designated demonstration vehicles only. Satisfaction of certification criteria would remove many requirements on operational vehicles. Thus, combined with a new reliance on designed-in margins and highly dependable parts and subsystems that are all certified to a much higher degree of dependability, we could eliminate “flight readiness-style” vehicle re-certification for every operational flight (as now performed on all major launch systems). An aircraft-style, vehicle-type certificate for repetitive commercial flight operations is envisioned. We will need to renew our space launch systems engineering infrastructure to meet this challenge, however (*see FINDINGS 7 & 8*). Until we see such certified designs come into operation with demonstrated reliability and obtain a high degree of confidence, land-locked spaceport concepts will be very problematic. In addition, without dependable and certified designs, the nation will be forced to support expensive maintenance and upgrades for “range safety” infrastructures.





## A VISION FOR TURNAROUND & THE ABILITY FOR YOU TO ACCESS SPACE

The nature of the current processes involved in turning around reusable launch vehicles (such as the Shuttle Orbiter and the recoverable Solid Rocket Boosters) is unacceptable for our future. The infrastructure and the operations for turnaround is labor intensive, equipment intensive, time consuming, and, due to ground and flight equipment dependability issues, fraught with a high degree of unplanned work.

Major functions involved with turnaround may include the following to varying degrees, depending on the vehicle concept and/or design:

- *Prepare facility for space vehicle arrival*
- *Receive vehicle at facility, position, secure and provide access*
- *Perform safing (ordnance, propellants, etc.)*
- *Perform inspections and checkout to verify no loss of vehicle certification for next flight*
- *Perform payload removal and installation*
- *Perform necessary component removals, replacements; conduct in-place repairs as needed*
- *Service commodities and perform close-out if desire*

In the future, the operations community would like a simplified, highly autonomous vehicle with much more dependable hardware performance. This would enable minimum periodic and repetitive maintenance (airplane-like) and result in short turnaround time between flights (hours, not months).

Further, we should strive to isolate vehicle ground operations from dependence on facilities and specialized equipment (spaceport infrastructure). Routine, scheduled turnaround should replenish consumables only. This will take a commitment to design the type of vehicle that operators and investors want. It will then take another commitment to build-in the dependability required. It will take yet another commitment to conduct comprehensive and disciplined one-time certifications for the flight and ground systems to earn the confidence needed to fly frequently, on-schedule and safely. Once achieved, however, space will open-up for all of us—even you!

# Ultimately... Space for Anyone



*Drama of Today's Spaceflight*



*Vision Spaceport artwork by Dan Rawlings*

*Investing in Opportunities for a Spacefaring People*

## SPACEPORTS AS BOTH EXPLORATION GATEWAYS AND COMMERCIAL TRADE PORTS

Spaceport concepts, such as those envisioned here, build on a rich history of development in transportation, trade and exploration. Consider the transportation capabilities built up during the Golden Age of Exploration, for example. New capabilities in sea-going trade and commerce fostered a new age in exploration for Western Europe in the Second Millennium. New shipyards, wharfs, port cities, as well as new ship types such as caravels, galleons and frigates emerged. Trends point to a future with improved spaceport throughput, new space destinations and markets, and a renewed purpose to explore and experience the space frontier. All this represents exciting new possibilities for our economic development.

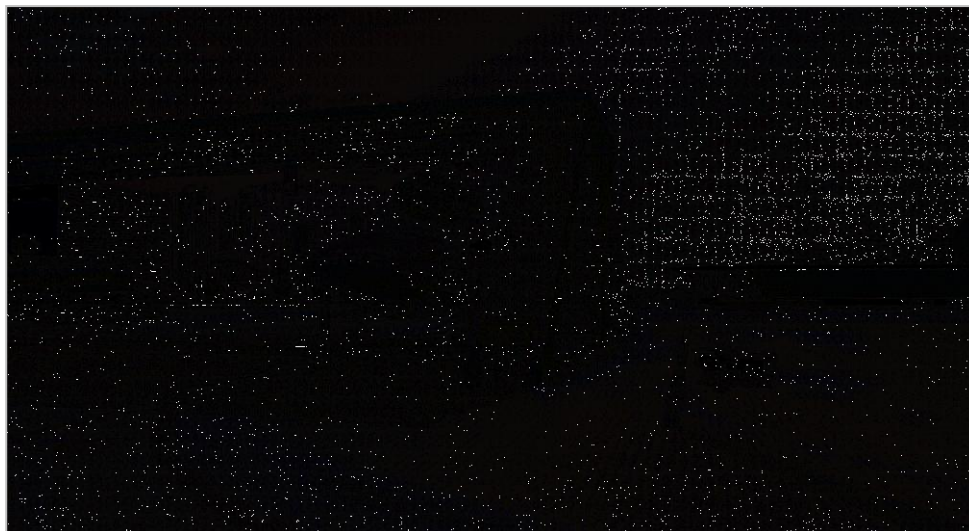


Spaceport architectural planning will need to consider innovative methods of transferring cargo and passengers from other earthbound modes of travel. Overland transportation (such as highways and rail), as well as air and sea cargo will need to come together with the “space-side” systems to create truly inter-modal transportation. With high flight rates, spaceports will become a common commercial “point-of-sale” between Earth and space.

An example, previously cited, is an opportunity associated with providing massive quantities of propellant needed for daily flights to and from a high performance spaceport. The concepts of co-production or poly-production not only offer promise in overcoming the challenge, but also provide large-scale economic opportunity. These dual-use concepts not only convert raw feedstock material into propellants, such as cryogenic hydrogen and oxygen, but also produce power for off-site consumption. The “poly-generation” concept uses coal to produce even more consumables, such as sulfurous-rich fertilizers and water. Many economic development opportunities exist for launch infrastructure and operations beyond that of a traditional “national range.””

### *Multi-Modal Space Trade Ports*

*Building on a Legacy of Transportation, Commerce and Exploration*





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## SUMMARY OF RESULTS

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### RESEARCH OBJECTIVES

Ultimately, the objective of the Vision Spaceport Project is to provide a foundation for strategically identifying concepts and technologies for advanced spaceport architectures, thus leading to follow-on research, demonstrations, and ultimately commercial development. While the tasks do not attempt to construct detailed spaceport "master plans," they are nonetheless creating the benchmarks, tools, basic model constructs, concept art, as well as analyzing strategic research and technology investments. The spaceport development community needs these products before making major master planning commitments. Therefore, follow-up focused spaceport master planning that uses Vision Spaceport research products, is a strategic outcome of this effort.

#### 1—BENCHMARKING LINE OF RESEARCH

The research team explored several levels of spaceport "benchmarking." The partnership learned early in the project that fundamental metrics relating to space transportation performance have not been collected into one common database and published on a regular basis [see FINDING 2].

##### *Top-Level Spaceport Performance*

The airline and airport industries track cargo and passenger throughput as a top-level metric for performance rankings.<sup>10</sup> The team researched launches for current vehicles and launch complexes. There are no such metrics or rankings publicly available and published by or for the space industry. Nor could the team initially find a single source that had adequate data to derive the throughput metrics<sup>11</sup>. The team found combining many different sources could provide insight into throughput performance.

The partnership conducted a minor effort to provide some insight by creating a database from different sources. However, due to the priorities of pursuing spaceport architectural modeling, technology analysis etc., the benchmarking effort focused more on identifying common measurable cost and performance parameters that reach across the spectrum of spaceport functions.

##### *Defining Benchmarks of Spaceport Functional Performance*

An early breakthrough in this line of research was reaching consensus among the government and industry partners on seven fundamental parameters:

1. *Facility Acquisition Cost*
2. *Ground Support Equipment (GSE) Outfitting Cost*
3. *Fixed Labor Cost*
4. *Fixed Materials & Other Direct Cost*
5. *Variable Labor Cost*
6. *Variable Materials & Other Direct Cost*
7. *Cycle Time*

These parameters reach across the life cycle spectrum of spaceport development and operational performance.

## *Benchmarking Generic Spaceport Functions—WHAT IS A SPACEPORT?*

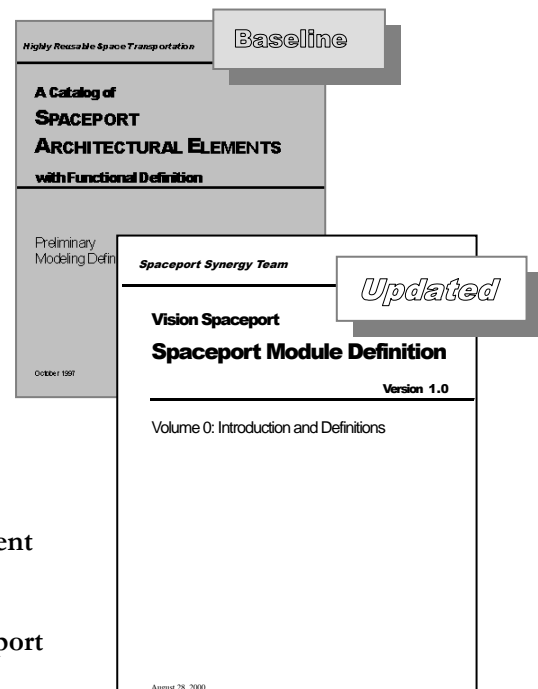
The Vision Spaceport partnership uses the term “spaceport” to refer to the facilities, equipment, personnel, and vicinity required (the infrastructure) to prepare space-bound vehicles and their payload for flight, initiate and manage the flight, and to receive them at the end of their flight (the operations). For earth-based spaceports, “vicinity” refers to the land (or sea) occupied by the launch infrastructure. For space-based spaceports, “vicinity” refers to the orbit and operations envelope of the space-based facilities. Dispersed infrastructure, spread over several locations, is a typical characteristic of spaceports. The dispersed infrastructure may include “downrange” instrumentation facilities, dedicated equipment and personnel for abort-mode landing sites, and space-based communications assets. Multiple spaceports may share certain resources.

The HRST study managers had previously challenged the Operations Sub-team to create a model for generic spaceports. While there were not enough resources to accomplish this at that time, the sub-team undertook a cataloging of generic functions as a necessary first step to first define a “generic spaceport.” The resulting *Catalog of Spaceport Architectural Elements with Functional Definition*<sup>12</sup> organized major spaceport functions in a hierarchy of sub-functions. This allowed the team to bypass, in the Vision Spaceport project, lengthy discussions attempting to define “what is a spaceport?”

While the hierarchy has remained intact throughout the Vision Spaceport project, the team improved the document by providing descriptive background, illustrations and photos of the top-level functional “modules.”<sup>13</sup> A particular Spaceport may or may not include all these functions depending on the customers and types of systems served. In the broadest sense, however, a future spaceport and planning for growth must consider all these functions for applicability and improvement. Additionally, the new 196-page document provides a structured vision for improvement that is consistent with the “orders of magnitude” being sought in current NASA space transportation plans. At the highest level, the catalog includes twelve major functional modules:

### *Major Operations & Infrastructure Functional Areas*

- Off-line Cargo & Passenger Services
- Traffic & Flight Control
- Launch
- Landing and Recovery
- Vehicle Turnaround
- Vehicle Assembly and Integration
- Vehicle Depot Maintenance
- Spaceport Support Infrastructure
- Concept-Unique Logistics
- Transportation System Planning and Management
- Expendable Element
- Connecting Community Infrastructure and Support Services





## GLOBAL SPACEPORT PERFORMANCE

In reviewing the many trade journals, almanacs, on-line databases, newsletters, etc., no single source made space transportation throughput visible as a published metric. Yet, when reporting airport and airline rankings, shipping port rankings, and almost all other forms of transportation, cargo mass per year and passengers per year are typically provided as measures of throughput. Throughput trends are also typically reported as indicators of industry health.

### LEADING SEAPORTS OF THE U.S.

Total Volume of Foreign Trade (Metric Tons)\*

(1) Houston-TX	92.3 Million Metric Tons
(5) NYC/New Jersey	50.8 Million Metric Tons
(9) Long Beach-CA	32.7 Million Metric Tons

\*Source: U.S. Bureau of Census, "U.S. Waterborne Exports & General Imports, Annual 1997" (Issued July 1998)



enco

### LEADING AIRPORTS OF THE WORLD

Total Volume of Cargo (Metric Tons)†

(1) Memphis-USA	2.4 Million Metric Tons
(4) Hong Kong	1.7 Million Metric Tons
(7) Frankfurt-GER	1.5 Million Metric Tons
(14) Amsterdam-NL	1.2 Million Metric Tons

†Source: Airports Council International-ACI, On-line Traffic Data: (<http://www.airports.org/traffic/index.html>); Prelim., 18 Mar 99



Channel Express

### LEADING SPACEPORTS OF THE WORLD

Total Cargo Mass Loaded & Unloaded (Metric Tons)‡

Cape Can./KSC-USA	~200 Metric Tons
Baikonur-KHA	?
Korou-FrG	?

‡Source: No known international trade sources that publish worldwide spaceborne cargo traffic from spaceports



NASA Photo

FIGURE 7— *Space Transportation System Throughput is a Major Indicator of Space Industry Health. The Questions are: 'Where are we?—What is the Trend?—How do we Improve?'*

## Spaceport Throughput and Throughput Efficiency

It is important to distinguish *throughput* from *throughput efficiency*. The maximum throughput achieved by the Space Shuttle system, for example, occurred around 1985.

In 1985, nine launches occurred with a total of approximately 300,000 lbs of payload and 50 crew members. Therefore, the Shuttle system achieved an *annual throughput of about 150 tons and 50 passengers per year*. At the same time, this metric of space launch performance indicates that Launch Complex 39 and its supporting ground infrastructure produced 150 tons of space cargo, while carrying 50 passengers.

Shuttle *throughput efficiency*, however, requires slightly different metrics. For example, one might look at the fact that no more than three shuttle Orbiters pass through any given hangar (or Orbiter Processing Facility-OPF) in a one-year period. Therefore, the *throughput efficiency of the Orbiter-OPF combination is about three flights per year per Orbiter, or three flights per year per hangar*. Changing throughput and throughput efficiency metrics gets back to the vehicle-to-ground system compatibility issue identified at the outset of this report—and why benchmarking throughput and throughput efficiency is so important to improving this nation's space launch performance.

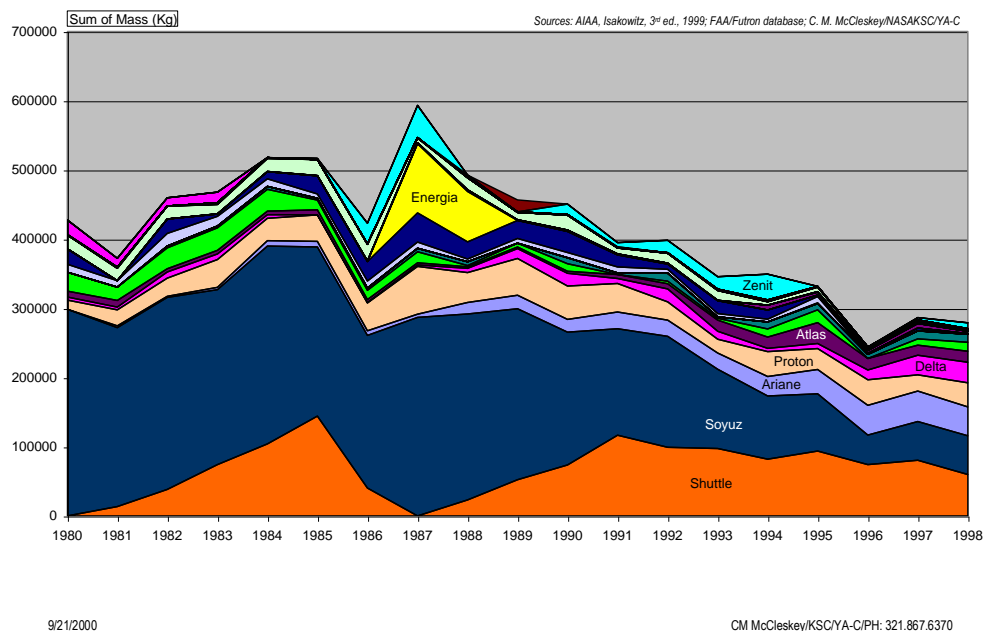
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*Changing throughput and throughput efficiency metrics gets back to the age-old vehicle-to-ground system compatibility issue—and why benchmarking throughput and throughput efficiency is so important to improving this nation's space launch performance.*

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## Spacelift Throughput Trend

*In Terms of Payload Mass (kg) from Earth to Space*



## *Defining Benchmarks for Reusable Launch System Performance*

Several key sources of information were used by the team to anchor our experience with existing systems to our model of spaceport functions. First, a breakdown of the Space Shuttle program budget elements, which was performed for the NASA Access-to-Space Study in 1994 helped to discriminate between labor and material costs.<sup>14</sup> For each program cost element, the team was able to identify a unique spaceport “module.” Fixed and variable cost relationships were obtained through a program element-by-program element analysis conducted by NASA in 1991.<sup>15</sup> While *Release 1* of the *Strategic Planning Tool* does not translate its output to dollars, summary data prepared by the NASA Technical Manager is provided in Table 1. (Again, note that this is raw data from the study and does not represent up-to-date program information. Plans for a *Release 2* will update, incorporate and validate Shuttle budget data). Other sources were found for facility acquisition (“brick & mortar”) and some ground support equipment outfitting costs. However, these sources were not considered comprehensive and, unfortunately, as with the other sources, extremely out of date.

The project team made a decision to output “figures-of-merit” only for the first release of tool. This was because only the Space Shuttle data was available across the spectrum of cost and cycle time categories, and since time to locate and analyze other launch systems within the resources of the project was not available. Comparative analyses between concepts are easily accomplished and are quite useful in early concept explorations. In fact, some of the partnership members are performing these types of comparisons are being performed by some of the Partnership members in NASA’s Space Launch Initiative.

GENERIC SPACEPORT MODULE¹	FIXED LABOR COST	FIXED MATERIALS COST	VARIABLE LABOR COST	VARIABLE MATERIALS COST	TOTAL
10—Trans Sys Plan'g & Mgmt	\$918.0	\$189.4	\$305.5	\$65.7	\$1478.6
9—Concept-Unique Logistics	\$366.0	\$181.6	\$138.1	\$157.1	\$842.8
8—Spaceport Spt Infrastructure	\$133.9	\$92.8	\$52.6	\$39.7	\$319.0
7—Vehicle Depot Maintenance	\$113.7	\$50.6	\$49.4	\$23.7	\$237.4
2—Traffic & Flight Control	\$77.6	\$55.6	\$34.4	\$32.8	\$200.4
5—Vehicle Turnaround	\$37.5	\$4.6	\$53.6	\$6.4	\$102.1
1—Offline Cargo/Pax Proces.	\$32.0	\$5.8	\$31.2	\$7.2	\$76.2
3—Launch	\$22.7	\$0.7	\$28.0	\$0.8	\$52.2
6—Vehicle Assembly & Integ.	\$11.2	\$0.5	\$12.0	\$0.3	\$24.0
4—Landing/Recovery	\$5.6	\$2.6	\$8.0	\$3.2	\$19.4
11—Expendable Element Proc.	\$1.2	\$0.0	\$1.8	\$0.0	\$3.0
Total Fixed	\$2303.6		-		↓
Total Variable	-		\$1051.5		
Total Labor	\$2434.0			-	
Total Materials	-	\$921.1			
TOTAL	\$1719.4	\$584.2	\$714.6	\$336.9	\$3355.1

TABLE 1—Space Shuttle Fixed and Variable Operations Costs Allocated to Generic Spaceport Functions

<sup>1</sup> Numbers associated with spaceport modules are references to the *Vision Spaceport Module Definition Document* (reference note 13).

### Modeling Goals and Objectives

The research and design of future generation launch vehicles continues as NASA and industry recognize the potential commercial uses of space and space-based transportation. However, potential applications and new markets will not materialize until there is a reduction in the cost of access to space by orders of magnitude<sup>16,17</sup>. In order to achieve this, and based on experiences with the only existing reusable launch vehicle (Shuttle) and several expendable launch vehicles, the design process has evolved and parameters like operability, maintainability, and life cycle costs are critical measures of performance for the evaluation of new architectures<sup>18</sup>.

The growing emphasis on affordability for space transportation systems requires the assessment of new concepts for all life cycle activities—from design and development, through manufacturing and operations. The project team explored the systems engineering processes involved in conducting operational assessments of launch concepts, focusing on modeling the ground support requirements of vehicle architectures, and estimating the resulting cost effectiveness and flight rate efficiency.

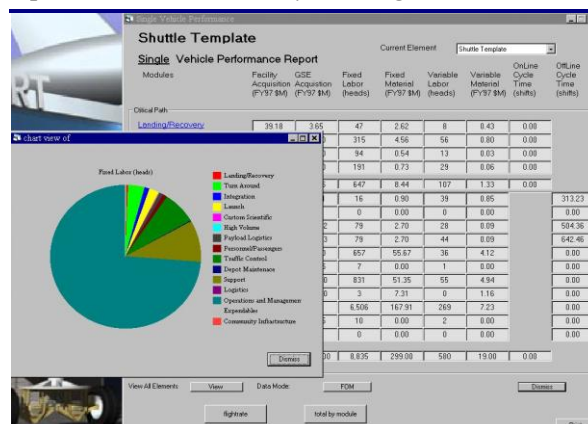


FIGURE 8— Modeling top-level cost and cycle time relationships of proposed space transportation concepts has been a key line of research in the Vision Spaceport Project

### Assessment Methodologies

The project team searched for modeling methodologies that were consistent with the expected level of concept input information and data availability needed to anchor the model or decision tool. This line of research turned up two promising approaches during the course of the project.

The first of these approaches resulted in a prototype model toolkit that assesses the spaceport requirements driven by a given space transportation architecture. The tools developed by this team provide a “sense of direction” and “order of magnitude” Life Cycle Cost (LCC) based on available benchmarks of the Shuttle program and other existing launch/transportation systems. The tools use *knowledge-based utility functions* that map vehicle characteristics to operational functions of a spaceport<sup>19</sup>, for example the *Launch* function referred to in the *Spaceport Module Definition Document*. The NASA team members in fact, successfully used the prototype tool for two NASA in-house activities; the Space Solar Power Concept Definition Study and the Space Transportation Architecture Study 99 (STAS99).<sup>20</sup>

A recommended advanced methodology was uncovered as an alternative approach. Dr. Alex J. Ruiz-Torres, of Florida Gulf Coast University, explored various innovative methodologies that apply to the infrastructure and operations modeling problem. Drawing from supply-chain management techniques employed in the manufacturing industry, Dr. Ruiz-Torres proposes the use of *activity-based cost modeling* for future assessments of space transportation architectures.<sup>21</sup> The modeling approach uses expert knowledge to determine the activities, the activity times and the activity costs based on proposed concept characteristics. The approach provides several advantages over current techniques to vehicle architecture assessment including easier validation and allowing vehicle designers to understand the cost and cycle time drivers.

### ***Visualization— Rendering Spaceport Concepts from a Functional Knowledge Base***

In addition to the challenges of analytical modeling, the Vision Spaceport research team also explored the techniques and technologies needed to render advanced spaceport concepts. For example, intelligent rendering of spaceport infrastructure might keep a running tally of fixed annual support costs, operational throughput efficiency, etc.

The **University of Central Florida's (UCF) Institute of Simulation and Training (IST)** has stepped up to this challenge. IST examined various advanced object-oriented software approaches and platforms. The key principle to observe in this line of research is constantly determining which technologies are compatible with both visual presentation techniques, interactive manipulation of generic spaceport functions, and display of life cycle cost and performance parameters.

The objective is to immerse the space transportation systems engineers in the spaceport domain, and to discover the infrastructure and operations implications, across the life cycle, of various systems solutions. This technology, then, becomes a graphical extension of analytical tools under development. Visualization technologies offer the possibility of positive and negative impacts uncovered and recognized early by the systems architects and engineers.

Some advanced visualization technologies explored and demonstrated were:

- Multi-dimensional visual benchmarking and terrain modeling
- Spaceport object attribute exchange protocols
- Information exchange across remote platforms
- 3-D systems that immerse engineers and potential customers in the spaceport environment
- Visual spaceport traffic and control tower environment simulation for exploring advanced spaceport architectures and operations concepts



FIGURE 9—Visualization technologies were explored and came together at NASA's Ames Research Center in its Flight Tower Central facility



### 3—Vision Spaceport Artwork

Another area pursued early in the project was the rendering of a shared far-term vision for spaceport operations by a highly acclaimed space concept artist. While there had been many renderings of launch vehicle concepts, it was very difficult to find artwork relating these concepts in the context of ground infrastructure and operations.

In previous years, the Spaceport Synergy Team had agreed on a vision statement for space transportation systems. Therefore, it seemed the appropriate time to entrust our common vision of operations to the capable hands of a space concept artist. The team was fortunate to bring Mr. Pat Rawlings of Science Applications International Corporation (SAIC) into the agreement.

Mr. Rawlings spent several days in September 1998, becoming familiar with launch and landing system facilities and functions. Subjects rendered by Mr. Rawlings included launch concepts, cargo and passenger conveyance, multi-modal operations concepts, as well as advanced concepts for traffic and flight control.

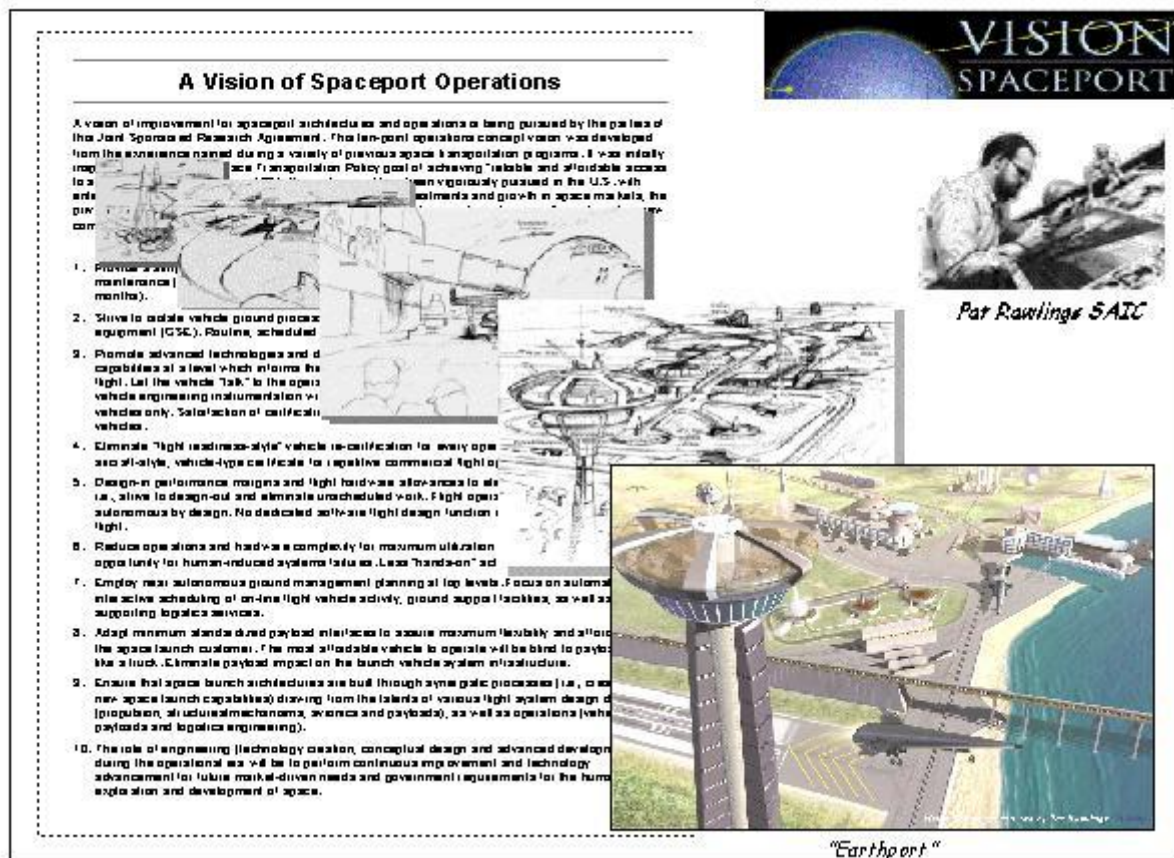


FIGURE 10— *Translating a Vision of Spaceport Operations into Art was a Challenge Confronted by the Partnership*

#### 4—SPACEPORT TECHNOLOGY ROADMAPS FOR SPACE SOLAR POWER

The Spaceport Synergy Team further explored its operations concept vision through its participation in the Space Solar Power (SSP) Exploratory Research and Technology (SERT) Program.

This effort focused purely on the ground infrastructure and operations challenges inherent in launching 35 million pounds of payload to space per year, and sustained at that rate for many years (ultimately at about \$100-200/lb). This implies very affordable, responsive, safe, and dependable spaceport architectures. It also implies specific technical advances in the state-of-the-art for spaceports. The Spaceport Synergy Team explored the technical challenges and has documented these in a separate report.

The national-level SERT Program defined reference configurations that represented near-, mid-, far- and very far-term operational scenarios. Within this context, the team was able to structure an approach to map out the *technology challenges* and systems development issues associated with the higher and higher throughput scenarios scoped out in the SERT program. Additionally, the approach needed to provide insight into specific programmatic factors relevant to the sequential timeframes, cost goals and capabilities explored.

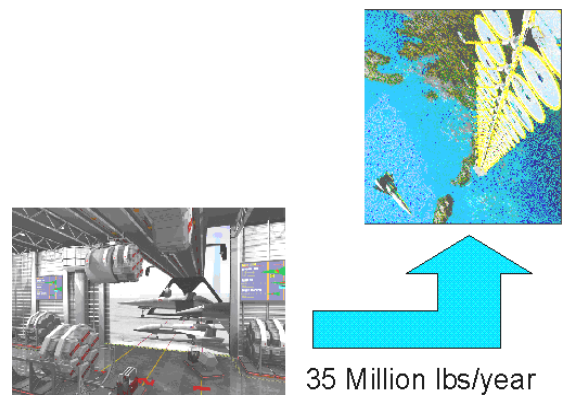


FIGURE 11—*Space Solar Power Systems Concepts Provided Unique Opportunity to Explore the Challenges of High-Throughput, Highly Affordable Space Launch Ground Infrastructures and Operations*

#### *Spaceport Technology Center*

Kennedy Space Center's Spaceport Technology Center (STC) initiative is designed to align and enhance existing KSC technology development product lines with the needs of future reusable and expendable space transportation systems. The Spaceport Technology Center initiative is an evolving component of KSC's Center of Excellence in Launch and Payload Processing Systems.

KSC's core business statement is to "Provide space systems processes, test, and launch techniques and develop associated technologies." As an active spaceport, KSC technology development activities encompass a wide range of technology readiness levels (TRL's). KSC has product lines for "spaceport design and systems development" which start with testing and integrating technologies at the mid-TRL ranges in order to build and deploy an operational spaceport system. KSC has also established unique development capabilities (personnel and laboratory/test bed facilities) for collaborative technology development efforts in several technology thrust areas. Historically, the majority of the total life cycle cost for any complex system is attributed to operational and support activities. Therefore, a primary strategy for reducing life cycle costs should be to develop and infuse spaceport technologies in future space transportation systems. KSC's complementary advanced spaceport technologies will benefit current and future spaceports on the earth, moon, Mars, and beyond.

The results of this effort are contained in the report *SPACEPORT CONCEPT & TECHNOLOGY ROADMAPPING: Investment Steps to Routine, Low-Cost Spaceport Systems*.<sup>22</sup> A summary of the recommendations are shown below:

*RECOMMENDATIONS From SERT Spaceport Technology Roadmapping*

1. A national policy of commitment to space transportation technology and infrastructure development is required
2. Investment in a modernized National Spaceport infrastructure in the areas of information systems, sensing and instrumentation, and command and control systems is required as a near-term step
3. Implement effective cost accounting, information, work control and tracking systems within the Cape Canaveral Spaceport. These systems should be pervasive, useful and fully a part of the systems being operated today on the National Ranges
4. NASA and the private sector must continue to develop, understand and mature customer requirements and opportunities, only one example of which Space Solar Power, leading to the maturation and stimulation of demand will that will take advantage of increased Spaceport capabilities
5. Institute a payloads customer and stakeholder initiative as a public and private sector partnership that addresses standardization, automation of test and checkout, carriers and containers for flight systems
6. Government and industry must evolve common support architectures compatible with a maximum or growing number of spaceports
7. Policy and regulatory frameworks must encourage capital availability
8. It is recommended that necessary next steps, that may be performed by government and industry partnerships, include a more detailed identification of impediments to the Spaceport improvements required



## ACRONYMS

AST	Associate Administrator for Space Transportation (FAA)
CCT	Command & Control Technologies Corporation
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
GSE	Ground Support Equipment
HEDS	Human Exploration & Development of Space
HRST	Highly Reusable Space Transportation
IST	Institute for Simulation & Training
KSC	Kennedy Space Center (Florida)
MagLev	Magnetic levitation
NASA	National Aeronautics & Space Administration
OPF	Orbiter Processing Facility
OSTP	Office of Science & Technology Policy
R&D	Research & Development
RLV	Reusable Launch Vehicle
SAIC	Science Applications International Corporation
SPST	Space Propulsion Synergy Team
TRL	Technology Readiness Level
UCF	University of Central Florida
USAF	United States Air Force



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- <sup>1</sup> Mankins, John C., *Aerospace America*, March 1998, pp.36-42 [hereafter, Mankins, *Aerospace America*]
- <sup>2</sup> Benson, C. D. & Flaherty, Wm. B., *Moonport—A History of the Apollo Launch Facilities and Operations*; NASA History Series, SP-4204; Washington, D.C., 1978. Online access from Kennedy Space Center: <http://www.hq.nasa.gov/office/pao/History/SP-4204/cover.html>
- <sup>3</sup> Top Left: Wernher von Braun and Kurt H. Debus—Top Right: The Apollo Management Council meets at NASA Headquarters in Washington, D.C. in 1967. Left to right are Dr. Wernher von Braun—Director Marshall Space Flight Center, Dr. Robert R. Gilruth—Director Manned Spacecraft Center, Dr. George E. Mueller—NASA Associate Administrator for Manned Space Flight, and Dr. Kurt H. Debus—Director Kennedy Space Center—Bottom: President John F. Kennedy during a briefing on Project Apollo at Cape Canaveral, Florida, November 16, 1963. Note that the models displayed convey a total system design with compatible flight and ground elements.
- <sup>4</sup> White House Office of Science and Technology Policy (OSTP), Presidential Decision Directives for National Space Transportation Policy (august 1994) & National Space Policy (1996).
- <sup>5</sup> Section 203(c)(5) and (6) of the National Aeronautics and Space Act of 1958 as amended.
- <sup>6</sup> NASA, Joint Sponsored Research Program—Program Information Package, April 1998
- <sup>7</sup> Rhodes, R. E., et al; RLV Operations Concept Vision and Operability Criteria Document, Encl. 3, Operations Synergy Team, 1994. Contributors were: B. Atkins, Martin Marietta-Michoud; R. Byrd, Boeing; Dr. J. Hanson, MSFC; J. Huether, Rockwell; C. McCleskey, NASA KSC; C. McCreary, NASA KSC; P. Scott, Lockheed; R. Vargo, McDonnell Douglas; G. Waldrop; Rocketdyne; E. Zapata, NASA KSC.
- <sup>8</sup> [KSC Co-gen and Polygen studies]
- <sup>9</sup> Zapata, E, et al, “Spaceport Concept and Technology Roadmapping,” Co-Gen Poly-Gen references from SERT white papers, November 2000.
- <sup>10</sup> Airports Council International—ACI, on-line traffic data; <http://airports.org/traffic/index.html>
- <sup>11</sup> Recently, however, the American Institute of Aeronautics and Astronautics (AIAA) published a third edition of the *International Space Launch Reference Guide*, Isakowicz, et al, 1999. It now lists payload mass per flight in its data, although, throughput performance summaries are still lacking.
- <sup>12</sup> *A Catalog of Spaceport Architectural Elements*
- <sup>13</sup> *Vision Spaceport Module Definition Document*, Version 1.0; Spaceport Synergy Team, JSRA NCA10-0030, September 2000.
- <sup>14</sup> NASA Access-to-Space Study, Space Shuttle Budget Work Breakdown Structure with Cost, 1994.
- <sup>15</sup> “Space Shuttle Zero-Base Cost Study,” Presentation to Dr. Lenoir, NASA Office of Space Flight, 1991.
- <sup>16</sup> Smitherman, D.V., compiler, *New Space Industries for the Next Millennium*, NASA CP-1998-209006, Marshall Space Flight Center, Huntsville, Alabama, December 1998.
- <sup>17</sup> O’Neil, D., Mankins, J, et al., *General Public Space Travel and Tourism—Volume 2 Workshop Proceedings*. Summary of a Space Act Agreement Study, including a workshop held at Georgetown University, Washington, DC, February 19-21, 1997. NASA CP—1999—209146, NASA Marshall Space Flight Center, Huntsville, Alabama, 1999.
- <sup>18</sup> Mankins, John C., “Lower Cost for Highly reusable Space Vehicles,” in *Aerospace America*, March 1998.

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<sup>19</sup> Zapata, E., and Ruiz-Torres, A.J. *Space Transportation Cost Modeling and the Architecture Assessment Tool- Enhanced*. IAA-99-IAA.1.1.01 paper presented at the 50th International Astronautical Congress, Amsterdam, The Netherlands, October 1999.

<sup>20</sup> *Ibid.*

<sup>21</sup> Ruiz-Torres, A.J. and McCleskey, C.M., *Operations Assessment of Launch Vehicle Architectures Using Activity Based Cost Models*, 1999.

<sup>22</sup> Vision Spaceport Partnership/NASA JSRA NCA10-0030, *Spaceport Concept & Technology Roadmapping: Investment Steps to Routine, Low-Cost Spaceport Systems*; NASA John F. Kennedy Space Center, Barker-Ramos Associates, Inc., The Boeing Company, Command and Control Technologies Corp., and Lockheed Martin Michoud Space Systems, November 2000.